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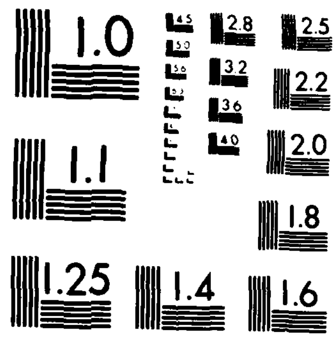
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COHERENT STRUCTURES IN TURBULENT FLAMES

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INTRODUCTION

The objective of this research was to obtain increased understanding of turbulent combustion in flows related to propulsion systems. Measurement and data analysis techniques, and the boundary conditions of various flames were designed to provide improved concepts and fundamental experimental data, to aid the development of modelling techniques for practical combustion systems. The Specific approach of the study was to quantify the roles of large eddies(coherent structures) in reacting flows. The experiments and measurement techniques which have been developed to attain this aim were described in previous Interim Scientific Reports. Measurements during the past year have been made in the initial region of gaseous jet flames with separate variation in Reynolds number and equivalence ratio. These measurements have produced detailed data on the structure of the initial regions of jet diffusion flames, as a function of systematic variation of initial burner nozzle conditions. This data is already recognized to be of considerable use for combustion modelling.

Two associated experiments, investigating the structures of turbulent liquid fuel sprays and impinging flames have been carried out during the period of the contract. These experiments also concentrate on the roles of eddy structure in controlling reaction in these types of flows. This report concentrates on the extensive fundamental data which has been derived on the structures of jet flames.

JET FLAME EXPERIMENT

Figure 1 shows the arrangement and notation for the jet flame experiment. The axisymmetric flame is produced by the flow of fuel gas through a 25.4mm diameter nozzle into a 400mm x 400mm, low velocity (0.73-1m/s), secondary air flow.

The experiments were designed to derive time dependent information from measurements of fluctuating quantities in diffusion flames. Fundamental information and insight are required on the "physics" of reacting flows and this information must be sufficiently extensive and accurate for use in attempting to model and predict turbulent combustion. A special effort was made in these experiments to carefully control, systematically vary and measure the initial and boundary conditions. By this means detailed measurements made in the flame can be compared directly with modelling predictions based on these boundary conditions. The burner nozzle is contoured to give a flat velocity profile at the exit with laminar internal and external boundary layers. The initial turbulence levels of both the primary (fuel jet) and secondary flows were less than 1%. Ignition and stabilization were in a laminar region near the nozzle lip. By progressively making measurements from the initial conditions at the nozzle exit, the natural development of the flame was followed , from the laminar conditions at the nozzle exit, through the transition region. The combination of high speed visualization and measured data show important deterministic features of the flows. Features such as burning interface layers, modes of stability of interfaces, reacting vortices and coherent large eddies were investigated by suitable measurement and data analysis techniques, including conditional sampling.

DIAGNOSTIC TECHNIQUES

Four main measurement techniques were used in the jet flame and these were developed to provide maximum accuracy and spatial and temporal resolution.

(i) Laser Doppler Anemometry (LDA)

This was used for measurement of mean and fluctuating velocity. Measurements were made in flows with velocities of the order of 10m/s and a frequency response of the order of 2kHz.

(ii) Fine Wire Thermocouples

A range of materials and diameters was used to construct fine wire thermocouples with digital compensation. A flat frequency response up to at least 2kHz was achieved with Pt/Pt Rh 25μm diameter wires.

(iii) Ionization Probe

Water cooled ionization probes were used to detect flame ionization and hence flame front location. Data on the frequency of flame front fluctuations were used for determination and interpretation of flame structure.[1,2]

(iv) Laser Schlieren

The LDA system was modified for use as a Laser Schlieren system. A single, 1mm diameter, laser beam was directed through the flame to strike a micrometer "knife-edge". Density related refractive index changes deflect the beam and a photomultiplier records the resulting light intensity variations beyond the knife-edge. The photomultiplier output is thus dependent on the integral of transverse density gradients, along the path of the laser beam.

High Speed Cine Photography

The high speed cine camera provides detailed qualitative pictures of the flame structure. Frame by frame analysis of the films provides quantitative information on the dimensions, velocities and passing frequencies of "events" in different regions of flames. The photographic information also provides the essential framework for the subsequent interpretation of fixed point measurements in terms of flame structure, where such structure has recognizable organization. Most of the High Speed Films have been taken using a color schlieren system with 600mm diameter mirrors.

EXPERIMENTAL RESULTS

The bulk of initial measurements have been made in a propane flame, Jet Flame I, under the following initial conditions at the nozzle exit: jet velocity, U_J = 6.4m/s; Reynolds Number, Re = 10^4; propane/air equivalence ratio, ϕ = 10.4. Measurements have been made in the first 20D of flame. Measurements have also been made with variation in Re and ϕ.

The 1978 scientific report[1] described the results of direct observations of the flame based on flame luminosity. The occurrence of vortex motions, distorting the flame, and the coalescence of these vortices beyond x = 16D was noted. However the more recent schlieren films and extensive point measurements have now revealed a flow structure which is considerably more complex than was first assumed. This complexity is caused by the simultaneous occurrence of several modes of instability near the nozzle so that more than one type of "coherent structure" can be observed at any one axial position. It has been found that the Kelvin-Helmholtz instabilities, which were at first assumed to dominate the transitional flame, are accompanied by equally important combustion instabilities which are mainly influenced by the physico-chemical properties of the fuel gas mixture, rather than the fluid dynamics.

Flow Visualizations

Color schlieren cine films have been made of a series of flames with, in the first instance, systematic variation in equivalence ratio, ϕ, with Reynolds number, Re, fixed. Subsequently ϕ was systematically varied while Re was maintained constant. This allows a separate study of the effects of fluid mechanical and combustion mechanisms in the transitional flames. The term "transition" refers to the transitional flow between the laminar region near the nozzle, to fully turbulent flow further downstream. The Reynolds number has been varied between 3 x 10^3 and 1.5 x 10^4. The equivalence ratio, ϕ, has been varied between ∞ ("pure" diffusion flame) and 1.5

(i.e. approaching premixed conditions). In all of the flames studied vortex-like structures could be detected in, at least, the first 20D of flow. Visually, these structures appear to be similar to those reported earlier[1,2,3] by the authors. Significant changes can be observed when both ϕ and Re are varied. Most of the data that has been analyzed to date is for "Jet Flame I", with Re = 10^4 and ϕ = 10.4. A general description of visualizations of this flame is given below. Quantitative data from the films is compared with point measurements later in this report.

The sketches shown in Figures 2,3 and 4 have been derived from frame by frame observations of the films and describe the general appearance of the first 15D of Jet Flame 1, divided for convenience into 5D sections. The most obvious feature seen on the films is a "double" structure in the first 20D, with inner fast moving eddies (Convection Velocity $\cong$ 6m/s) and outer, large, slow moving eddies (Convection Velocity < 2m/s). The inner eddies have the appearance of hot/cold interfaces developing wave instabilities. These interface-waves coalesce and interact: wave amplitudes, wave lengths and spacings between waves all increase with increasing distance downstream. The outer vortex-like eddies, which are also indicated by hot/cold interfaces, develop much more slowly. There appears to be no observable correlation or interaction between the outer and inner vortices up to about x = 10D. However, beyond this position, the outer eddies appear to encroach increasingly into the centre of the jet and there is an obvious complex interaction between these two instability modes. The outer hot flow region has been termed the "pre-heat zone" (Figs. 2,3 and 4) and the inner interface has been termed the "reacting interface". This pre-heat zone can be clearly seen in the classical photograph of Wohl, Gazley and Kapp.[4]

With increasing distance downstream there is an increasing growth of "three-dimensionality". This is observed, first by vertical "streaks", and later by "cellular" interface structures, reminiscent of schlieren photographs of turbulent premixed flames (e.g. Lefebvre[5]). Photographs taken by direct photography, using flame luminescence, show that the initial streamwise streaks are similar to those observed in cold jets[6] in which vortex rings develop azimuthal waves as one of the stages in the transition process. Films of flames with varying ϕ indicate that the local thickness of the "preheat zone" increases as ϕ decreases; as the jet mixture ratio is made leaner, the stoichiometric mixture "line" moves further in towards the jet centre. Varying ϕ also changes the frequencies of the inner vortices; this important effect is discussed in the section describing the laser-schlieren measurements. Increasing Re resulted in the more rapid onset of three-dimensionality, and thus, presumably, a reduction in the transition length of the flame.

Interpretation of the schlieren films was hampered by the inability to interpret line-of-sight integrated data unambiguously in terms of point information. At first sight, the films give the impression of providing a cross-sectional view of the flame in a radial plane, perpendicular to the optical axis. The initial laminar flame has a thin

cylindrical shape so that most of the observed information indicates the flame structure. As instability develops, radiation from the "front" and "back" parts fo the flame is recorded on the film.

Velocity Measurements

Cold Jet I, the air jet with the same Re value as Jet Flame 1, was studied in detail by using a hot wire anemometer. The nozzle boundary layer is laminar[2] with a "shear thickness" $U_J(\delta U/\delta r)^{-1}_{max}$ = 2.36mm. The nozzle exit turbulence level is 0.4%, and these small fluctuations occur mainly at a frequency of 30Hz, which is assumed to be the resonant frequency of the jet settling chamber. The initial instability frequency of the mixing layer is 215 Hz which is within 5% of that predicted by the theory of Michalke.[7] Hot wire frequency spectra in Cold Jet I showed the appearance of subharmonics, and thus a vortex ring coalescing region, between x = 2D and x = 4D. The frequency spectra approach the turbulent form beyond x = 4D, indicating that this is the transition length of the cold jet.

Figure 5 shows LDA measurements of mean velocity in Cold Jet I. The data is in excellent agreement with hot wire measurements, and also with previously reported measurements. This indicates the good general accuracy of the LDA system. This data was obtained without frequency shifting so that inaccuracies are possible (particularly for fluctuating velocity data) where the mean velocity falls below 2m/s. The potential core of Cold Jet 1 ends at $x \cong$ 4D.

Figure 6 shows mean velocity profiles in the first 20D of Jet Flame 1. These results are in dramatic contrast to the data shown in Figure 5, for the non-burning flow at the same Reynolds number. The potential core in the flame, as indicated by the central uniform velocity region, now apparently extends beyond x = 20D. The centre line velocity changes little in magnitude in the first 20D length of flame. Mean velocity gradients are generally higher in the flame, than at the same axial position in the cold jet. However, the total width of the flows does not differ greatly between the flame and cold cases, for any particular x value. Examination of individual velocity profiles in the flame reveals, at some stations, the occurrence of "humps" in the profiles, i.e. more than one inflection point is found compared with the classical single inflection point, error function or Gaussian shapes in the cold jet. These and other differences between the cold and burning flows need to be explained in terms of the various phenomena introduced by chemical reaction and heat release. Attention is being focused initially on the effects of combustion on the relatively orderly structure of the transitional flows; in the first place to obtain a qualitative understanding of the various processes, and secondly to derive quantitative data on these individual processes for eventual comparison with predictions with the aim of developing more accurate computer modelling techniques.

Figures 7 and 8 show profiles of fluctuating velocity, $(\overline{U^2})^{1/2}/U_J$, measured by LDA in Cold Jet 1 and Jet Flame 1 respectively. A special experimental problem arises in

measuring turbulence intensity in the vicinity of peaks in the region very near the nozzle ($x = 0.04D$). In this region, an anomaly is introduced by the relatively large LDA measurement volume when compared with the shear layer thickness. LDA measurements do not agree with hot wire data which show turbulence levels less than 1% across the complete flow in this region. In common with most published investigations using LDA, the LDA turbulence levels tended to be higher than those measured by hot wires by a factor of $U_J/100$, approximately. Thus a 1.5% turbulence level measured by LDA corresponded to a 0.5% level measured by hot wires. This overestimation of turbulence level by LDA is a result of an accumulation of errors and biasing inherent in all LDA systems.[8]

The turbulence distributions in Figure 7 are in good agreement with those reported previously in cold round jets, using both hot wires and LDA. Peak turbulence levels occur near the end of the potential core at $x \cong 4D$ followed by a decay, approaching the slope x^{-1} for exact similarity. The flame core, Figure 8, is quite different, with a much slower increase in turbulence levels with increasing distance downstream. However, the maximum levels at $x = 20D$ are higher than those found in the cold jet, i.e. 20% as opposed to 15%. Furthermore, there is every likelihood of further increases beyond $x = 20D$. The peak turbulence levels in the flame are found nearer the outer low velocity stream and there are relatively small turbulence levels along the centre line of the mixing layer at the nozzle lip radius. Double peaks in the turbulence distributions are seen up to $x/D = 6$ in Figure 8. These could be connected with the interactions of vortices or waves in the transitional flame. These results show that there is a significant influence of combustion on the turbulence field in the initial region of the flame. Further work is required in order to explain these findings and develop models which are consistent with these phenomena.

In two-stream mixing flows, such as those investigated here, it is necessary to provide uniform seeding in both streams so as to avoid biasing effects in LDA measurements. The influence of changing seeding particle number density in each stream has not been reported in any detail in the literature. A series of tests was carried out in which the relative seeding densities of the primary and secondary flows were progressively varied. Very significant changes could be produced in measured mean and r.m.s. velocities, depending upon the relative seeding levels, and the position in the flow. This indicated the need for careful equalization of seeding levels before each set of experiments. Separate from the problem of making accurate measurements of time averaged quantities, controlled changing of seeding levels can be used to derive conditionally sampled velocity data which can be interpreted in terms of intermittency and fuel/air mixing. Figure 9 shows an example, in Jet Flame 1, in which mean velocity profiles are measured with, (i) primary flow seeding only, (ii) secondary flow seeding only and (iii) both flows seeded. In general the "primary seeding" velocity is higher than the local mean velocity, and the "secondary seeding" velocity is lower. This agrees with what could be expected from intermittency

sampled data obtained in mixing layers in the past, by using hot wires. It is interesting to note that the primary flow (including the products resulting from burning of this primary flow) penetrates only to the centre of the mixing layer up to the edge of the potential core. Mixing, and thus reaction, can only occur in the region of overlap of the two streams, i.e. approximately 7mm $\leq r \leq$ 18mm at x = 6D. It will be shown that this corresponds to the region of high ionization levels.

Ionization Levels

Measurements of ionization levels have been made in Jet Flame 1, including mean values, r.m.s., p.d.f.'s and frequency spectra. Problems of calibration drift, condensation and sooting of the probe have been encountered; these create particular difficulties with regard to fluctuating ionization density measurements. These problems have now been largely overcome in the new designs of probe. Distributions of mean ionization level are shown in Figure 10. It is seen that the region of significant ion density is relatively narrow, compared with the total mixing layer width indicated by the mean velocity distributions. High ionization levels indicate high rates of reaction at elevated temperatures. Comparison of Figures 9 and 10 shows that the regions of overlap of the primary and secondary flow seeding particles (where mixing takes place) correspond with regions of high ionization levels. Peak signals are found near x = 6D. Interpretation of signal magnitude is not straightforward because of the complex dependence on probe geometry, flow velocity and reacting layer width, as well as ion density. The sensitivity of the ionization probe, to the occurrence of reaction, makes it a valuable tool for studying the transitional flame, where convoluted, reacting interface layers are clearly visible.

LDA mean velocity and ionization probe measurements at x = 8D in Jet Flame 1 are compared in Figure 11. It is interesting to note that there is a "hump" in the mean velocity profile near the peak ionization level position. This can be explained as being due to flow acceleration accompanying reaction and heat release.

Temperature Measurements

Temperature measurements have concentrated initially on a detailed mapping of the mean temperature field of Jet Flame 1 using fine wire thermocouples with digital processing and radiation corrections. Figure 12 shows mean temperature profiles in Jet Flame 1. The peak mean temperature is found near x = 3D. The temperature peak moves progressively away from the centre of the jet flame and, beyond x = 3D, decays in value with increasing distance downstream. The peak temperature is always further from the jet centre than the peak ionization level (c.f. Figs. 10 and 12). The separation between the two peaks increases with increasing distance downstream. At each station, the total local mixing layer width, indicated by the mean temperature data, lies within 10% of the width indicated by the velocity profiles.

Laser-Schlieren Data

Laser-schlieren spectra have been measured at different longitudinal positions in Jet Flame 1, with the laser beam passing through the flame, tangential to a cylindrical projection of the nozzle lip ($r = 0.5D$). These spectra represent integrated data for the complete length of the beam, and they thus contain contributions from values of r greater than 0.5D.

Figure 13 shows spectra measured at four axial stations. Distinct peaks are found, corresponding to the regular wave and vortex structures seen in the schlieren films. Several distinct peaks are found at each axial station; in general, there are no clear harmonic relationships between the frequencies at which these peaks occur. Peak amplitudes of the distinct frequencies rise to maximum values at $x/D \cong 4$ and then decline with distance downstream. This is in some accord with the appearance of subharmonics of the initial Kelvin-Helmholtz instability in spectra in the transitional cold jet.[2] However, there are important and significant differences between the cold and flame cases; this is made clear by the results of a series of systematic experiments in which Re and ϕ were varied.

Figure 14 shows spectra obtained when Re was fixed and the equivalence ratio ϕ was varied. It can be seen that there is a gradual decrease in the most energetic frequency as ϕ was increased by increasing the proportion of fuel in the propane/air mixture, while maintaining a constant exit velocity. Similar results were obtained at higher Reynolds numbers, but the most energetic peaks then occurred at higher frequencies. Figure 15 shows spectra obtained by maintaining a fixed equivalence ratio and varying the Reynolds number (i.e. varying the primary flow rate). It is seen that, for all Re, there are a series of distinct peaks in the spectra, but the frequency values of these peaks are <u>independent</u> of Reynolds number. It is deduced that the inner vortices, which distort the initially laminar reacting interface layer (Fig. 2), cannot be simply explained as being due to Kelvin-Helmholtz instabilities, as generally found in cold jets, even if account is taken of heat release. Rather, it appears that combustion-driven instabilities are generated which result in wave and vortex structures similar in appearance to the Kelvin-Helmholtz vortices.

Thus there is a series of discrete frequencies at which the inner instability can occur and the values of these frequencies depend on the physico-chemical properties of the fuel gas. The flow rate (i.e. Re) determines the frequency, or batch of frequencies, from this series in which most of the energy is concentrated.

The simultaneous occurrence of frequency peaks without clear harmonic relationships indicates that there is more than one possible mode of instability occurring for any particular flame. It should be noted that the initial conditions of the jet flame are essentially laminar and there were no indications, in the cold jets, of the peak frequency values found in the flames. Furthermore, tests showed that the frequency spectra were insensitive to the application of an external sound field. This

indicates that the initial instabilities result from a powerful mechanism which cannot easily be interfered with by the imposition of acoustic waves (due to fans, instruments etc.).

Figure 16 shows the peak frequencies found in Jet Flame 1. The most energetic peak was found to change to lower frequencies by discrete "jumps" with increasing distance downstream. Prior to the laser schlieren experiments, and the insight provided by their spectra, a series of schlieren movies of Jet Flame 1 were analyzed for eddy passing frequencies along a line above the nozzle lip. These data are included in Figure 16 and the agreement is seen to be remarkably good. Thus the vortices clearly seen on the inner side of the mixing layer are responsible for the spectra peaks. Analysis of cine films requires subjective judgement at times, and there is inevitably a "smearing out" of the coalescing, or other processes, responsible for the transfer of energy between discrete frequencies. Beyond x = 10D, the dominant frequency is near 30Hz, and this is considered to correspond with the encroachment of the large, slow moving, outer vortices across most of the width of the mixing layer.

COMPUTER MODEL

A mathematical model of the unstable shear layer in an axisymmetric flame jet has been developed using a vortex approach to model the large coherent structures observed in jets. This time-dependent model focuses on the initial region of the jet where the laminar flow develops instabilities which eventually give rise to the fully turbulent flow downstream.

The model follows the motion of the fluid by following individual fluid elements in the flow which constitute a Lagrangian grid. These elements are carefully selected so that attention can be concentrated on the region in which mixing, heat release and temperature fluctuations occur, i.e. the shear layer. The basis for the mathematical model has been developed from the concept whereby a vortex sheet can be described by discrete vortices.

Initially the cold flow has been investigated, in which a cylindrical vortex sheet in an unbounded domain becomes unstable. To make the calculations, a periodic disturbance has initially been given to the sheet and the development of the disturbance followed. As can be seen in Figure 16 the initially well- defined grid becomes distorted with increasing time due to the build up of numerical errors. In order to overcome this problem it is necessary to redefine the grid at certain stages in the flow calculation.

CONCLUSIONS

Accurate measurement techniques, with good resolution, carefully designed flows, with known and controlled boundary conditions, and systematic variation of input variables, have been used to gain fundamental data on, and insight into, the structure

of turbulent flames. A double-vortex structure was found: with outer vortices, which may originate from Kelvin-Helmholtz or Rayleigh type instabilities, and inner vortices which are influenced strongly by one or more combustion instability mechanisms. Although most data have been derived for the first 20D near the burner nozzle, there are clear indications, from cine films, that the coherent structures which originate in this region can still be traced near the end of the visible flames (40D to 100D depending upon the values of ϕ and Re). The application of multiprobe and conditional sampling techniques are used to measure the detailed structures of the observed interacting instability waves and vortices. Because of the complex but apparently deterministic nature of most of the flow, more effort is now being applied to time dependent computer models, which attempt to include the various observed physical phenomena. The insight and data provided by this study should enable eventual improvement in the accuracy of predictive techniques for practical combustion systems.

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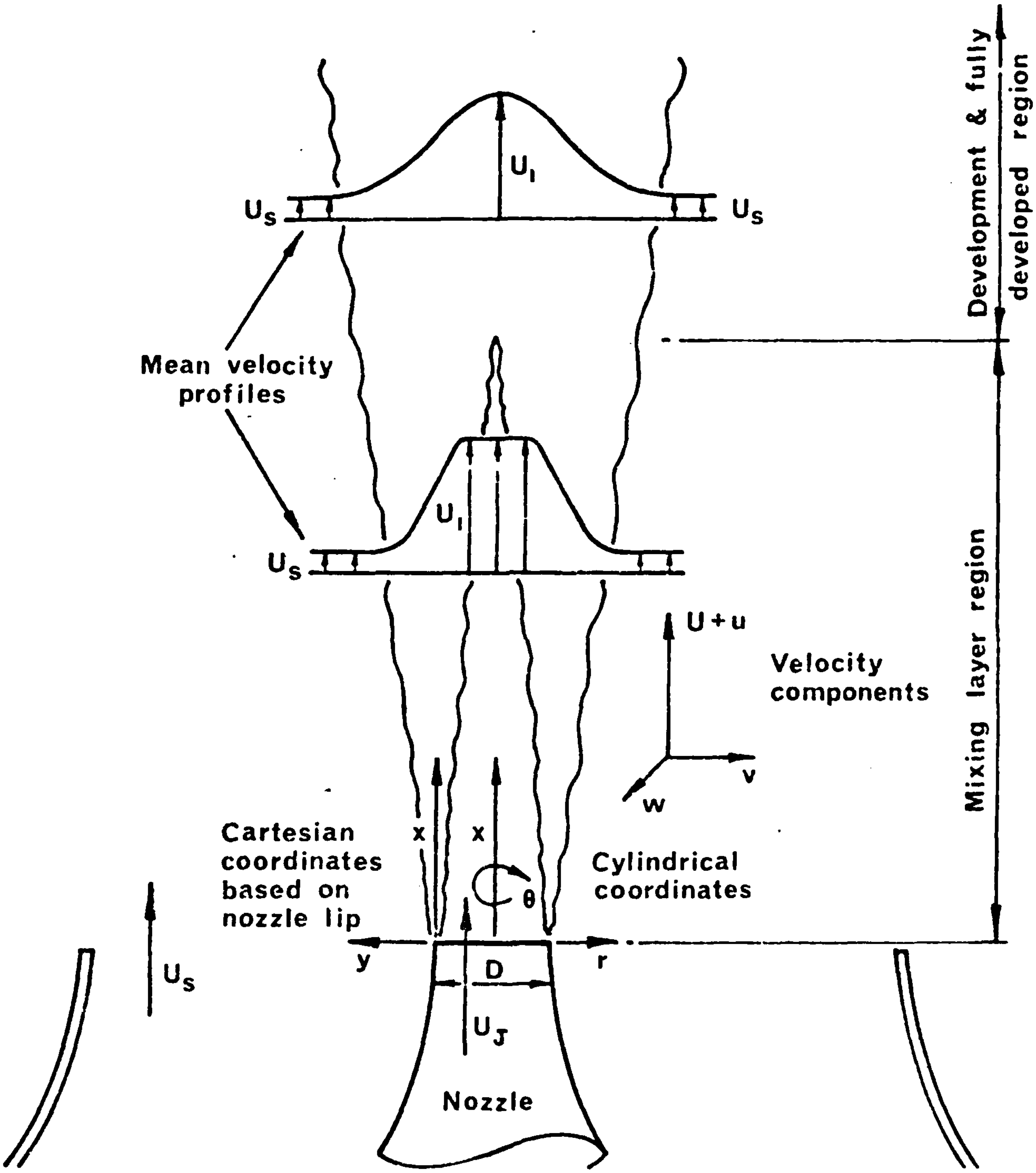


FIGURE 1. Notation for axisymmetric jet flame experiment.

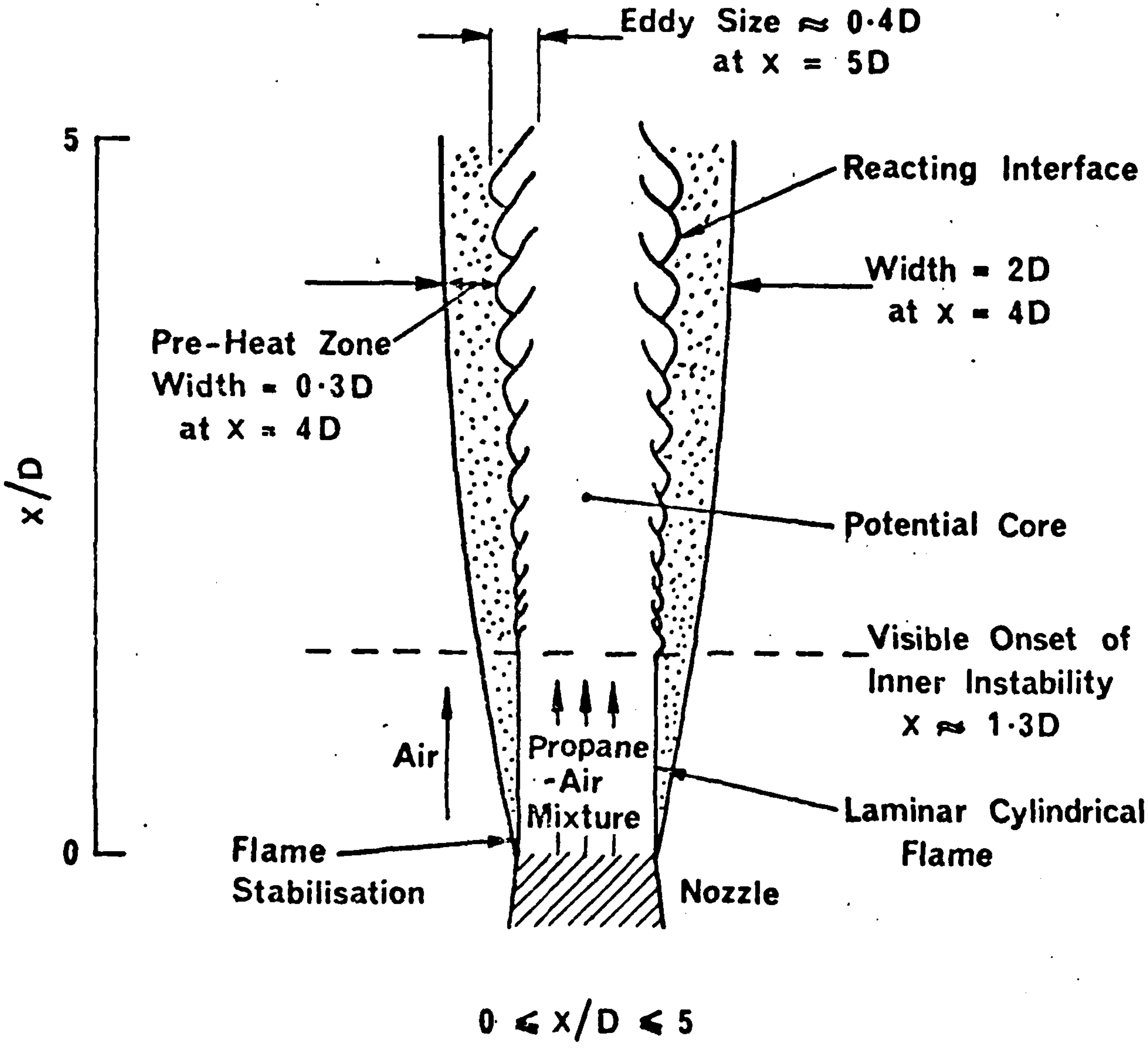


FIGURE 2. Visual appearance of Jet Flame 1 between 0D and 5D. Sketched from schlieren movies.

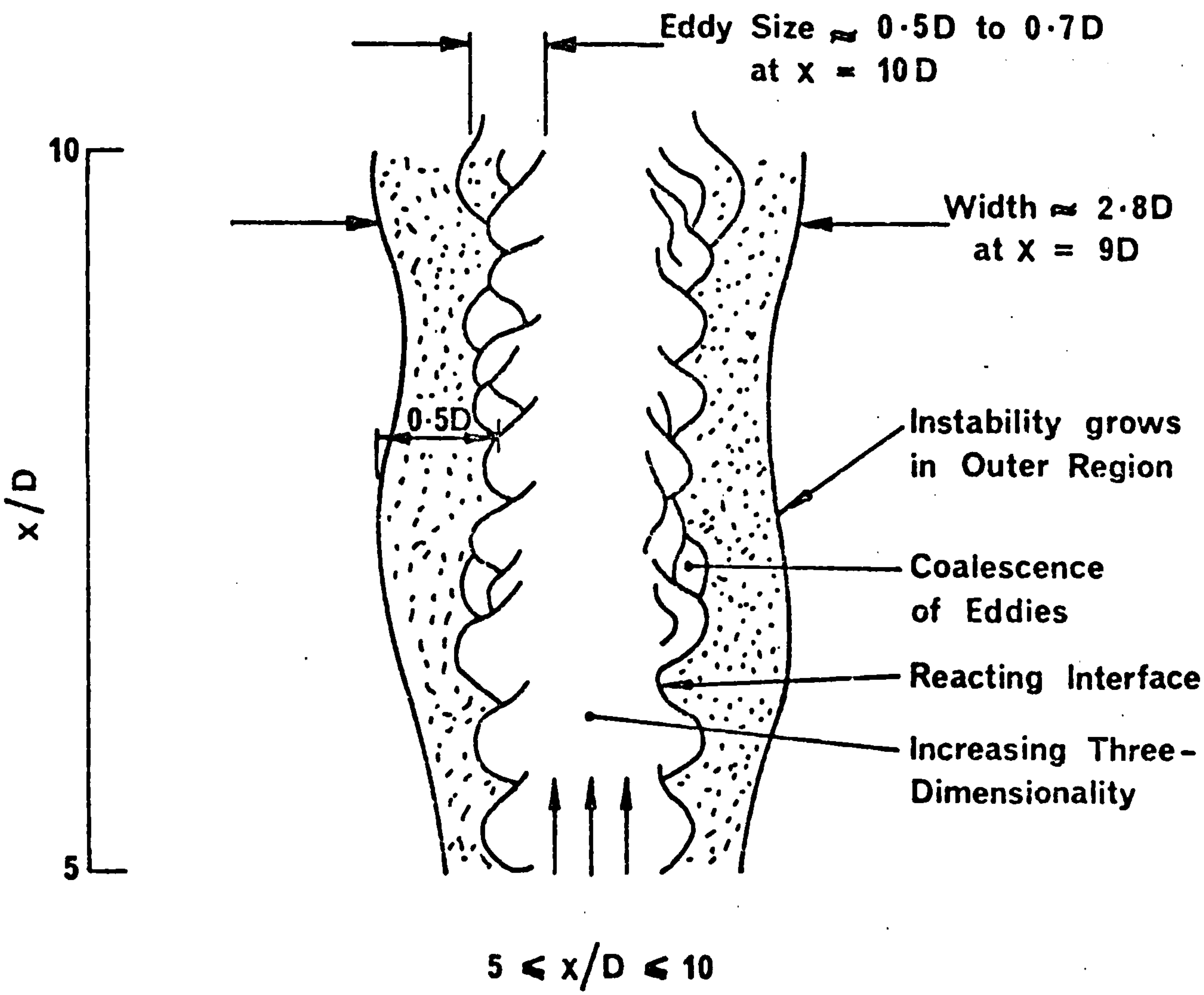


FIGURE 3. Visual appearance of Jet Flame 1 between 5D and 10D.

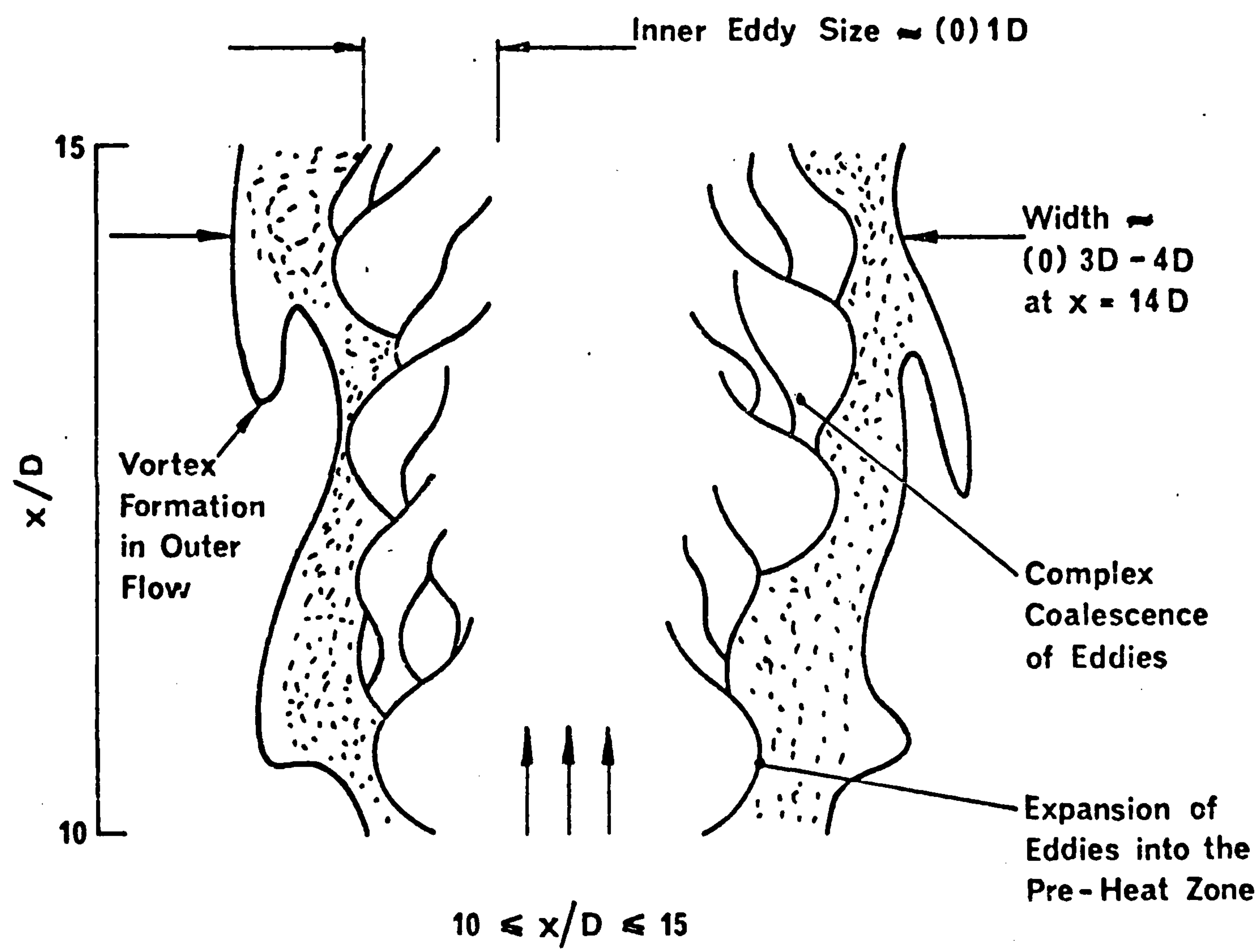


FIGURE 4. Visual appearance of Jet Flame 1 between 10D and 15D.

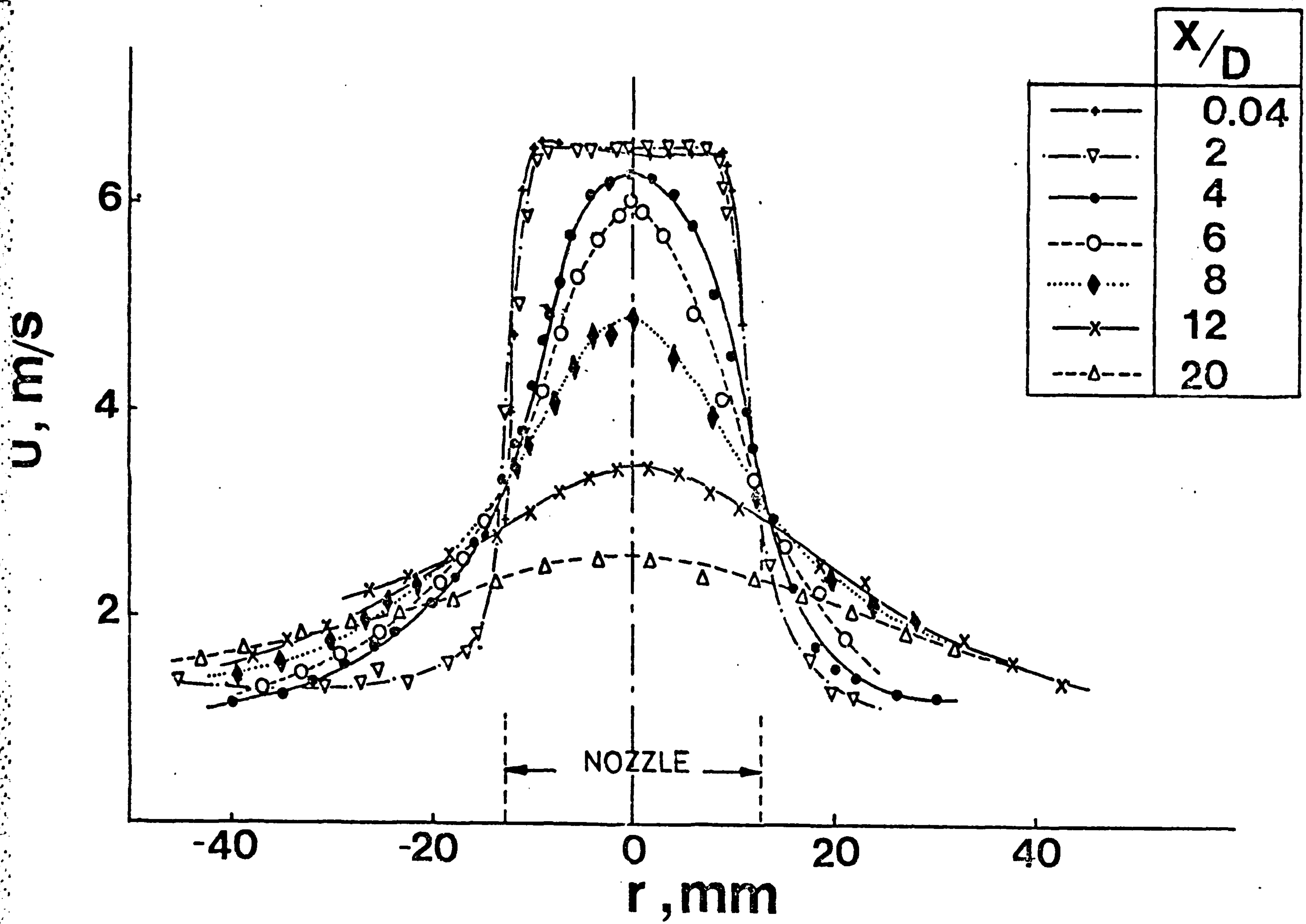


FIGURE 5. Measurements of mean velocity in Cold Jet 1 by LDA. ($Re = 10^4$)

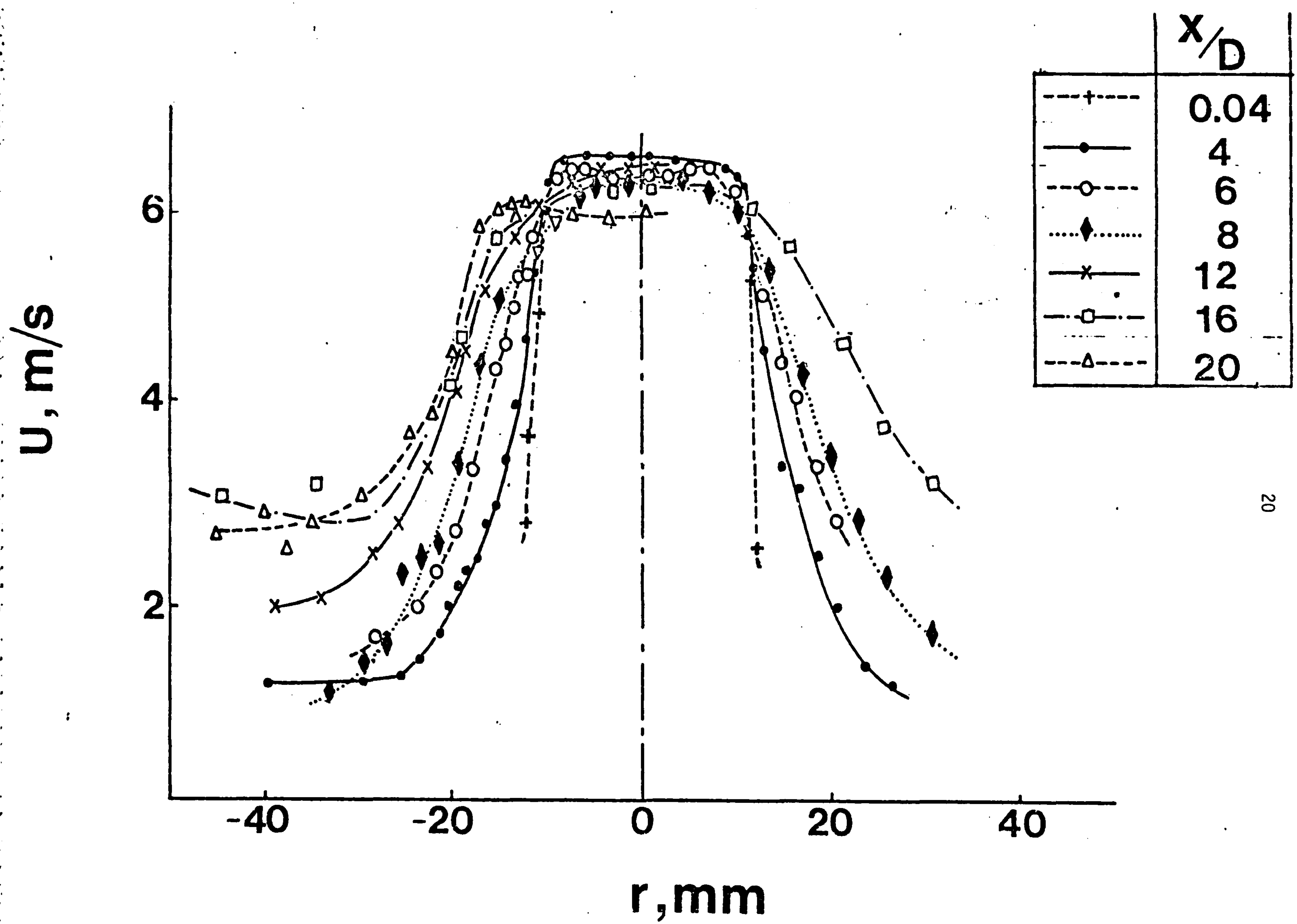


FIGURE 6. Measurements of mean velocity in Jet Flame 1 by LDA. (Re = 10^4, ϕ = 10.4)

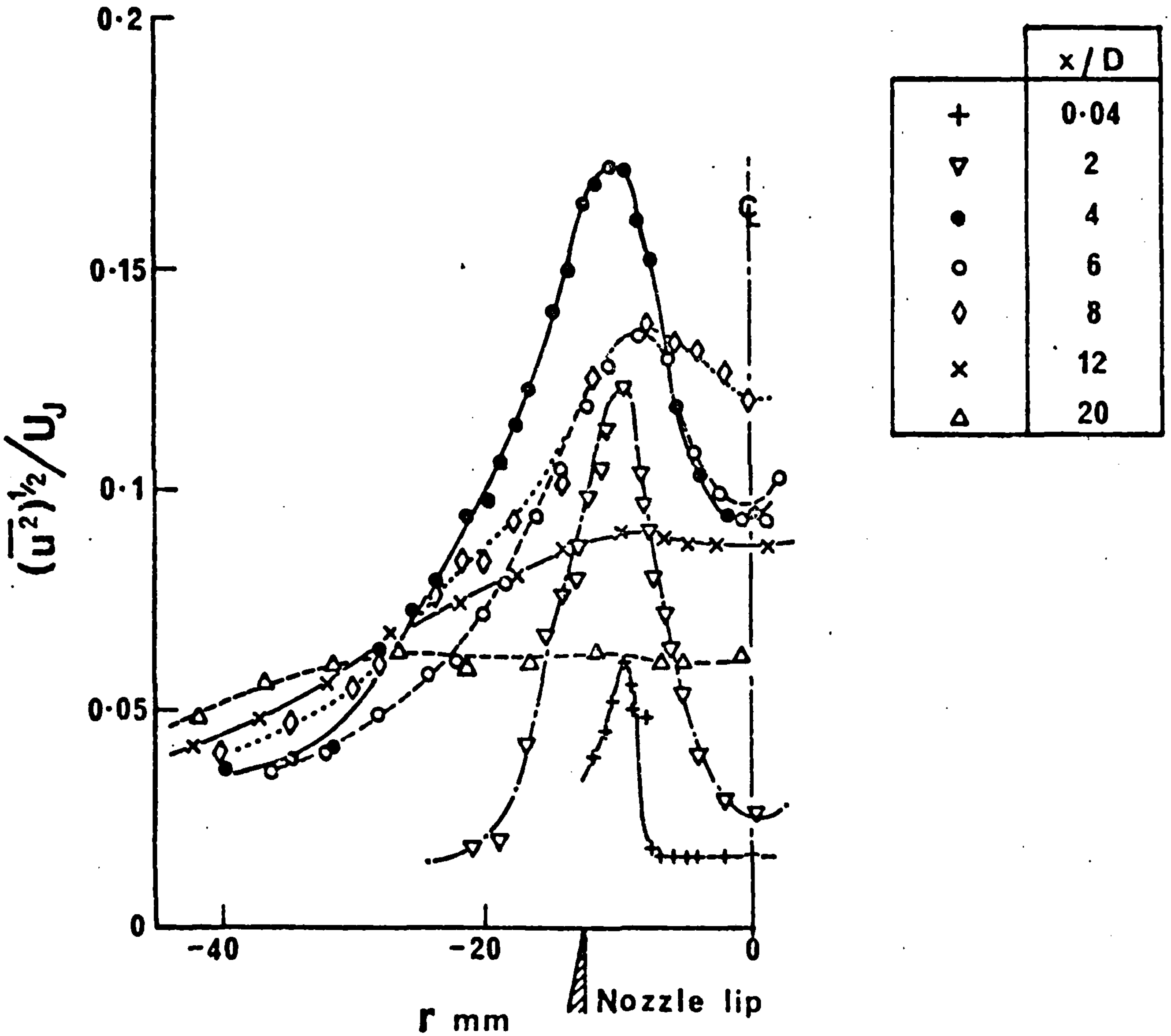


FIGURE 7. Measurement of turbulence intensity in Cold Jet 1.

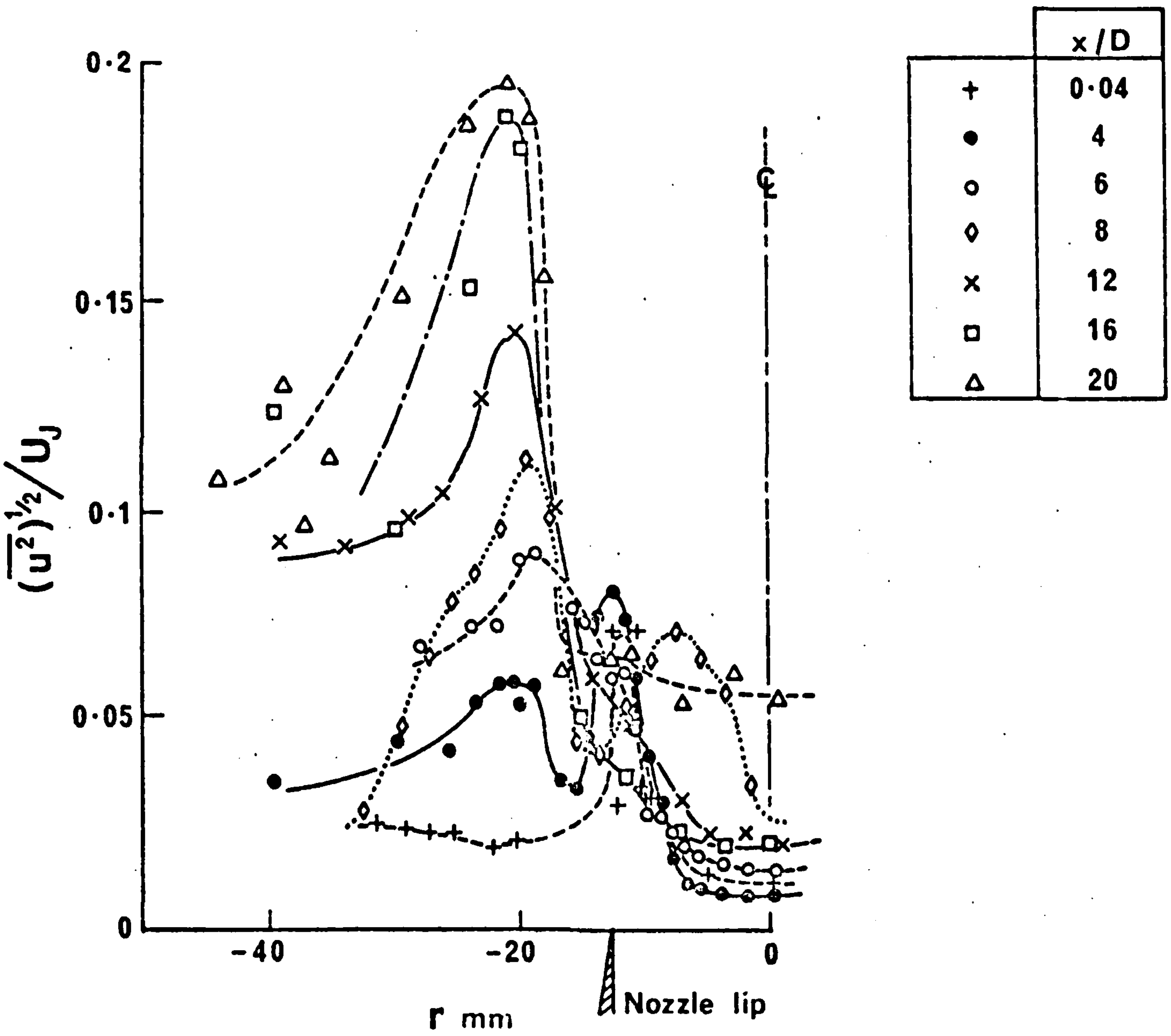


FIGURE 8. Measurement of turbulence intensity in Jet Flame 1.

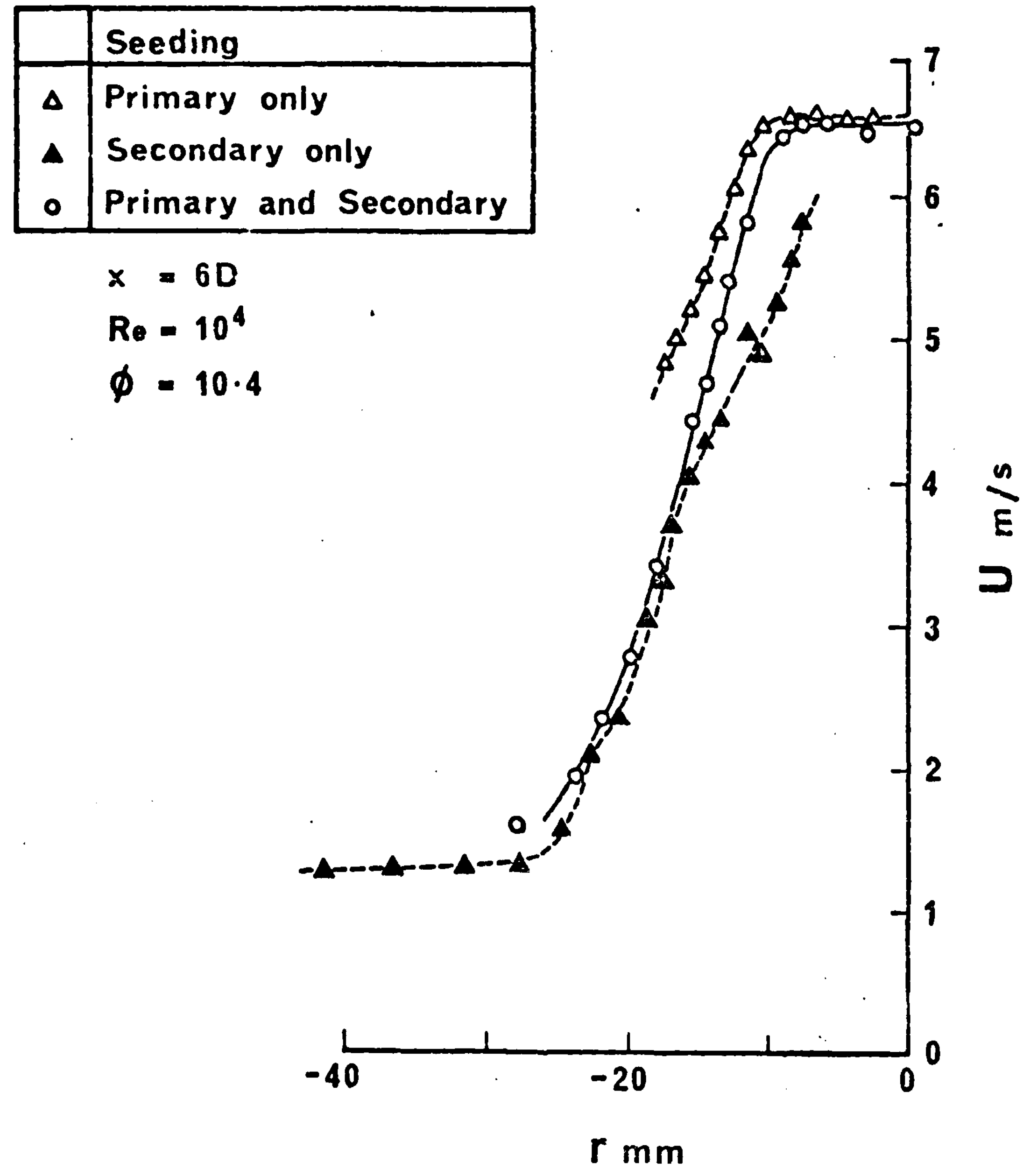


FIGURE 9. Mean velocity profiles measured in Jet Flame 1 for different modes of seeding.

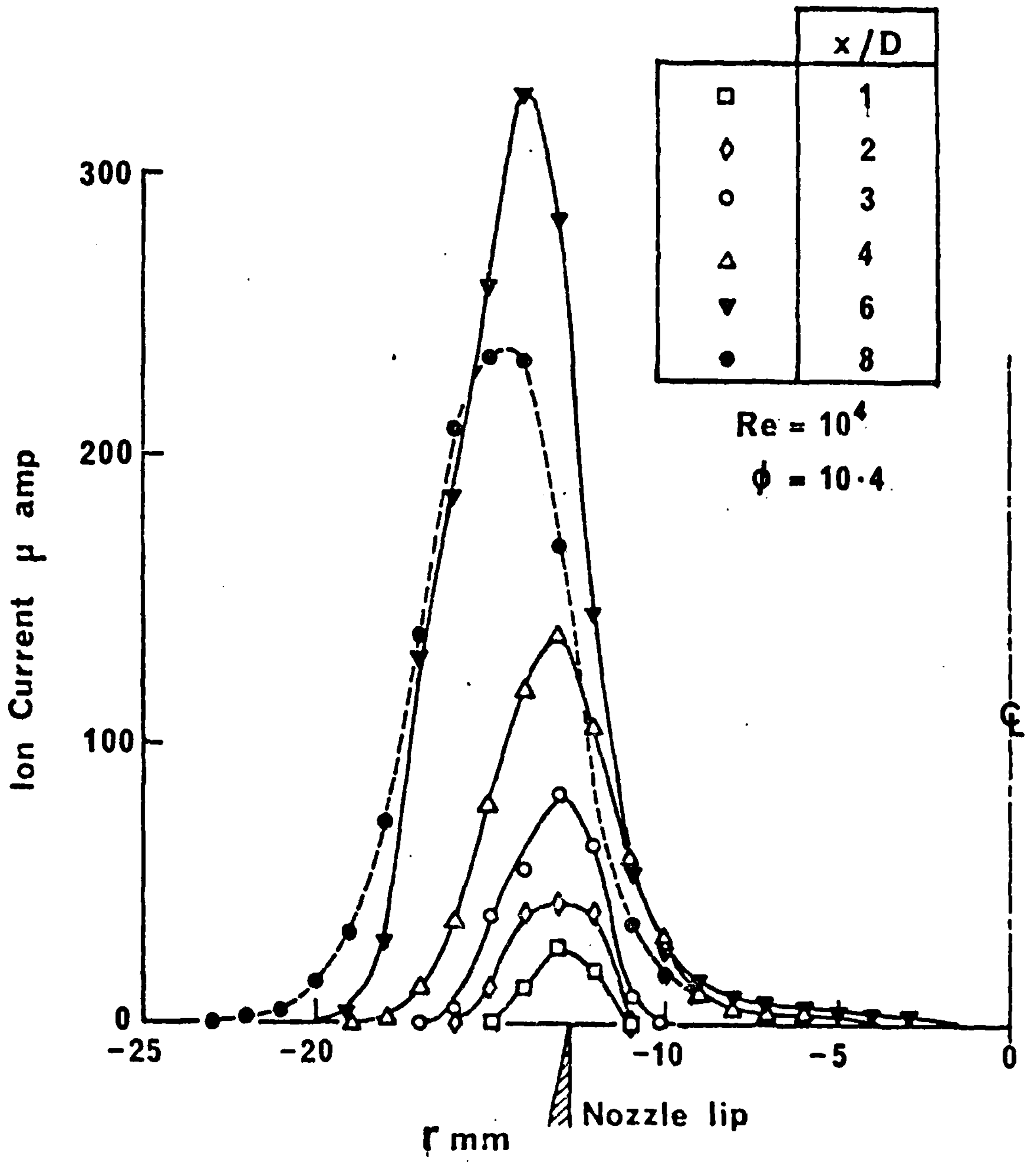


FIGURE 10. Measurements of mean signal from ionization probe in Jet Flame 1.

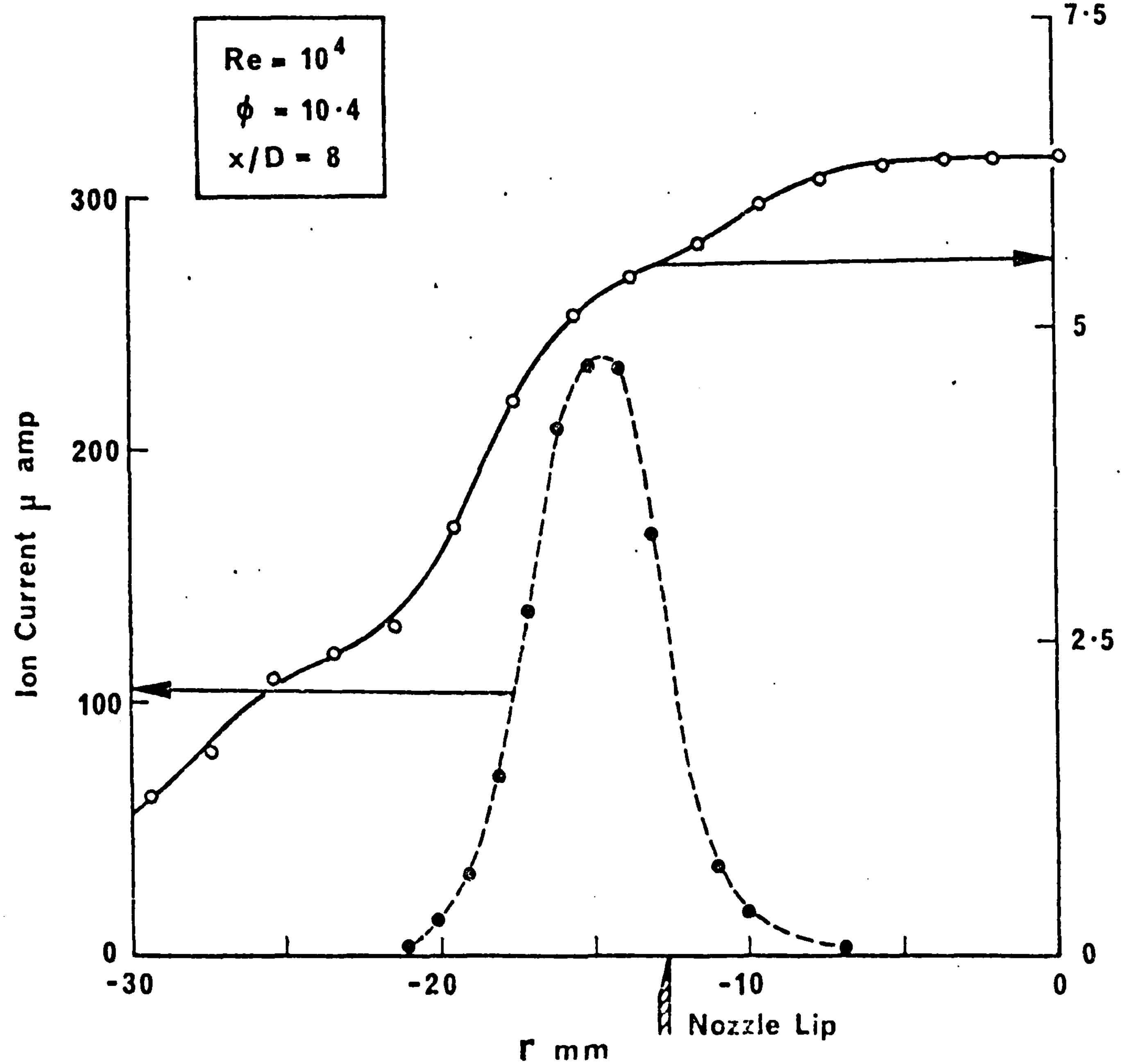


FIGURE 11. Comparison of mean velocity and mean ion current profiles in Jet Flame 1.

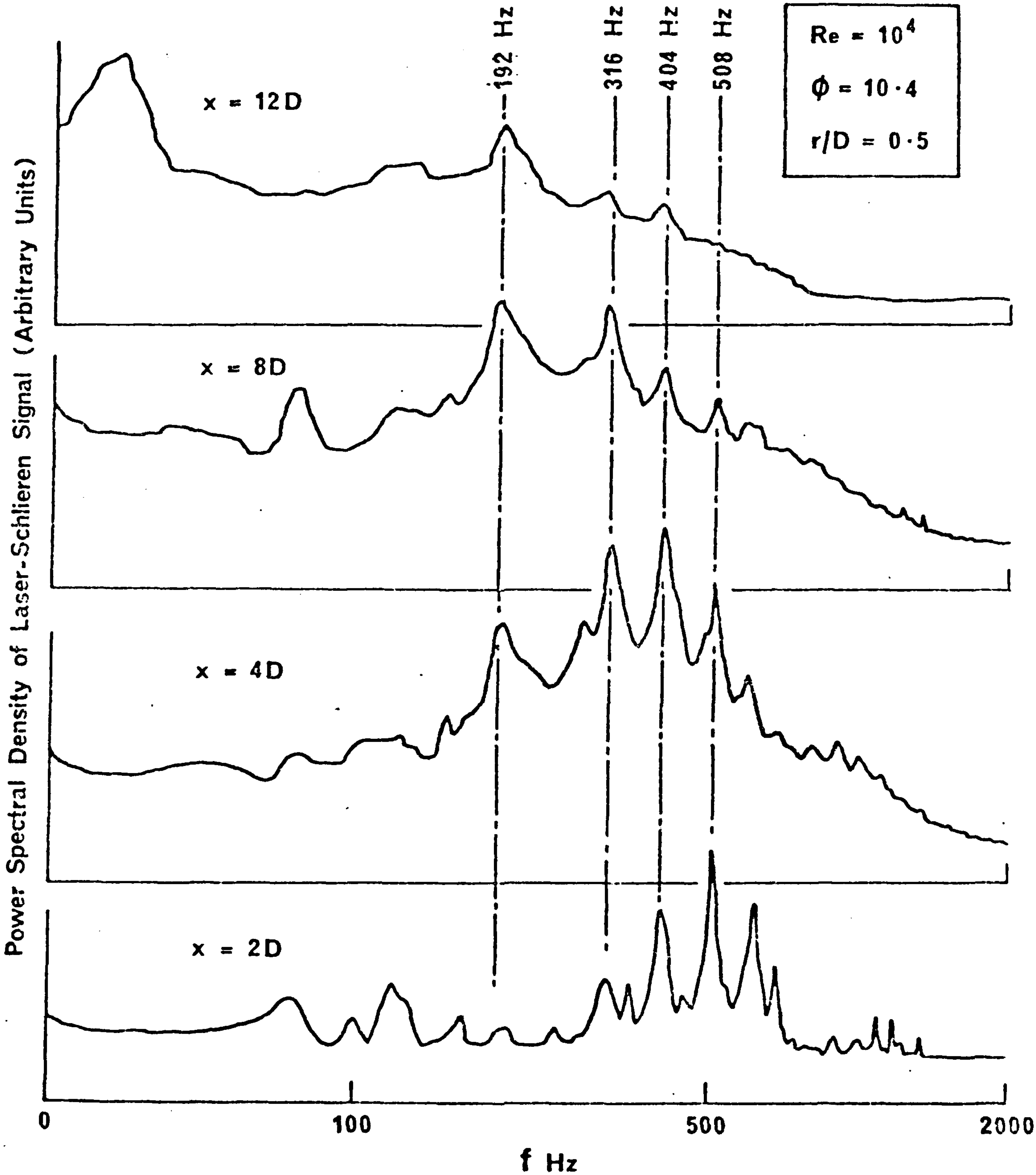


FIGURE 13. Spectra of laser schlieren signals in vertical line above nozzle lip in Jet Flame 1. (Log/Log plot)

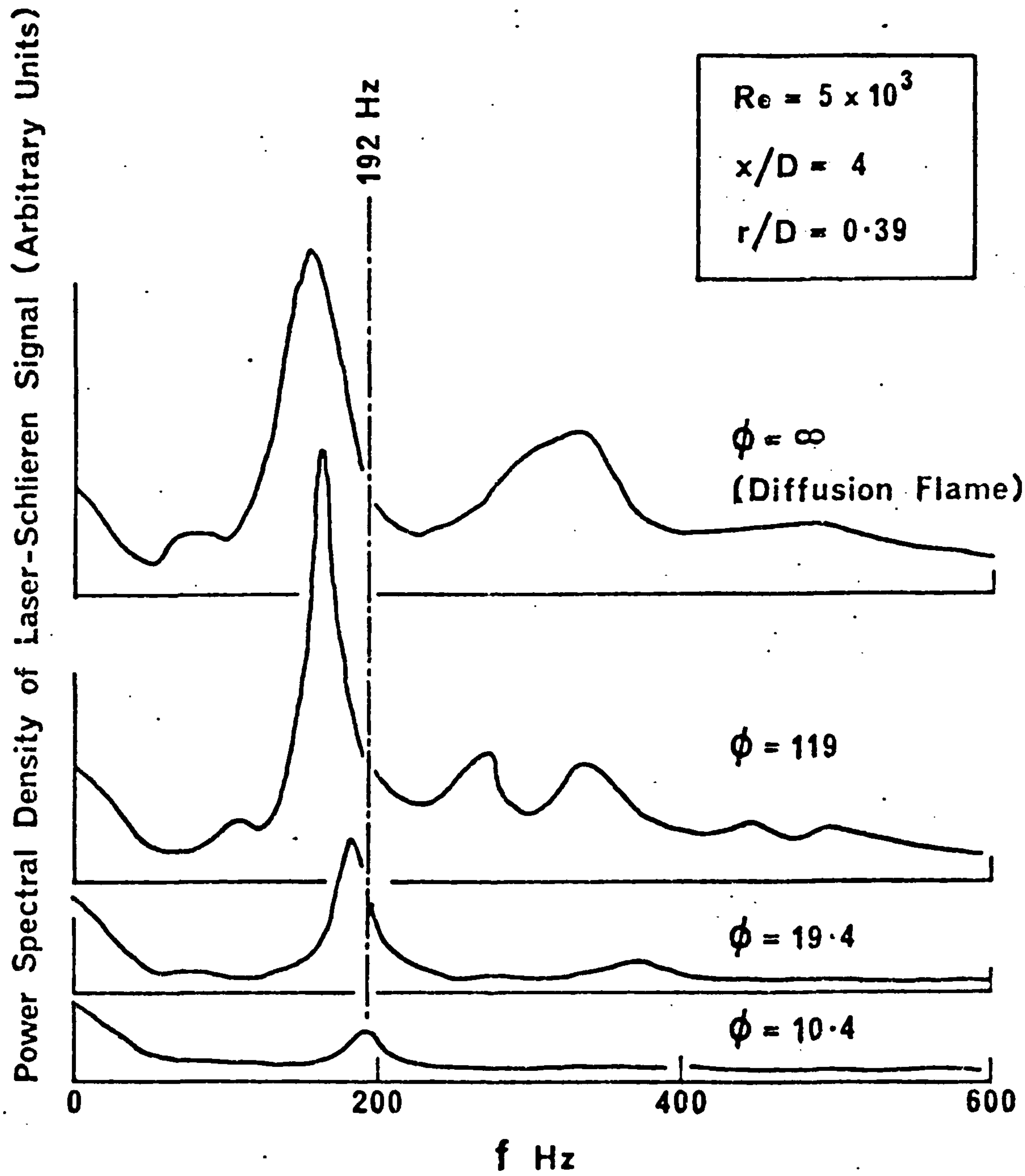


FIGURE 14. Laser schlieren spectra at fixed position and Reynolds number (5×10^3) with variation in jet equivalence ratio.

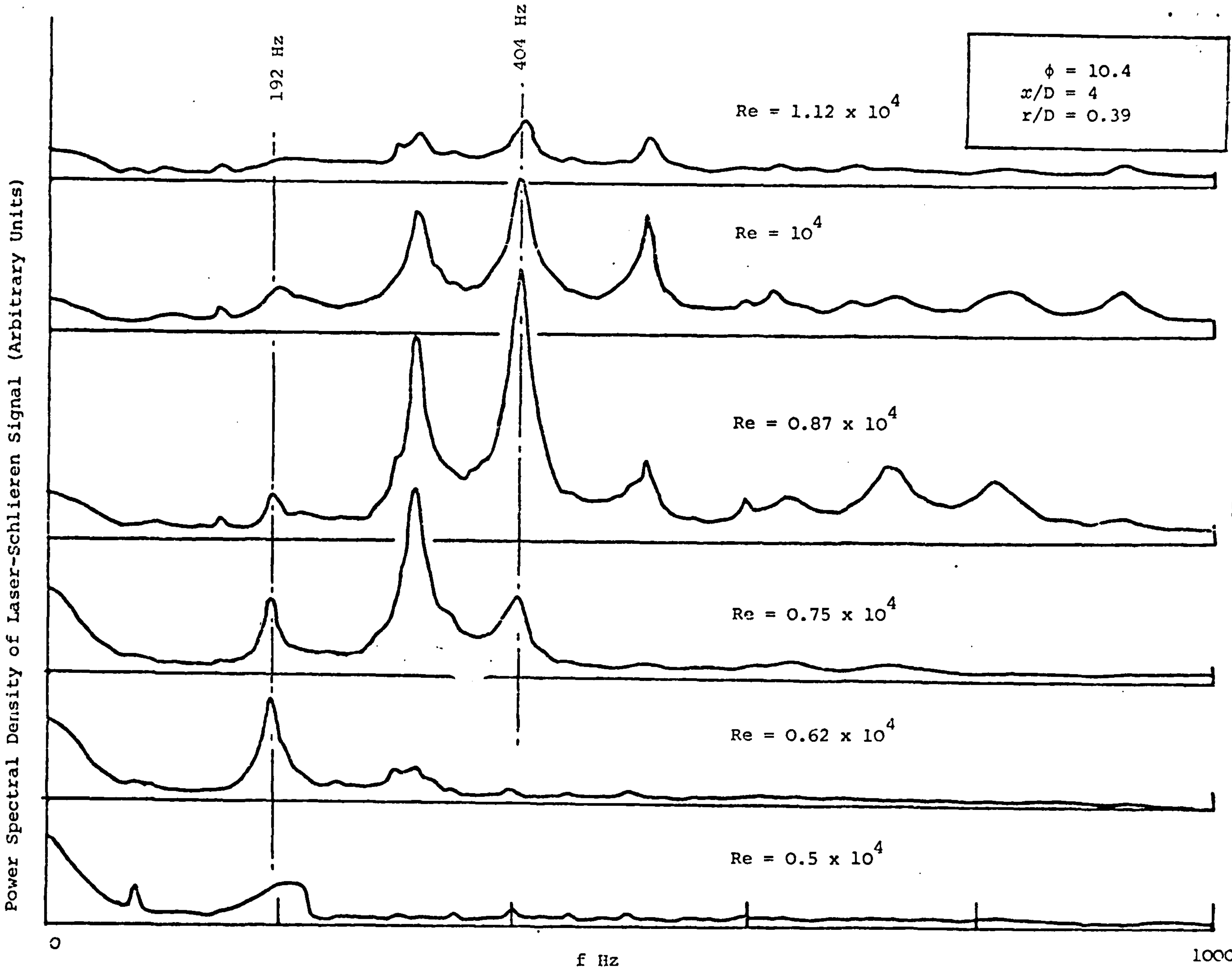


FIGURE 15. Laser-schlieren spectra with variation in Reynolds number at fixed equivalence ratio.

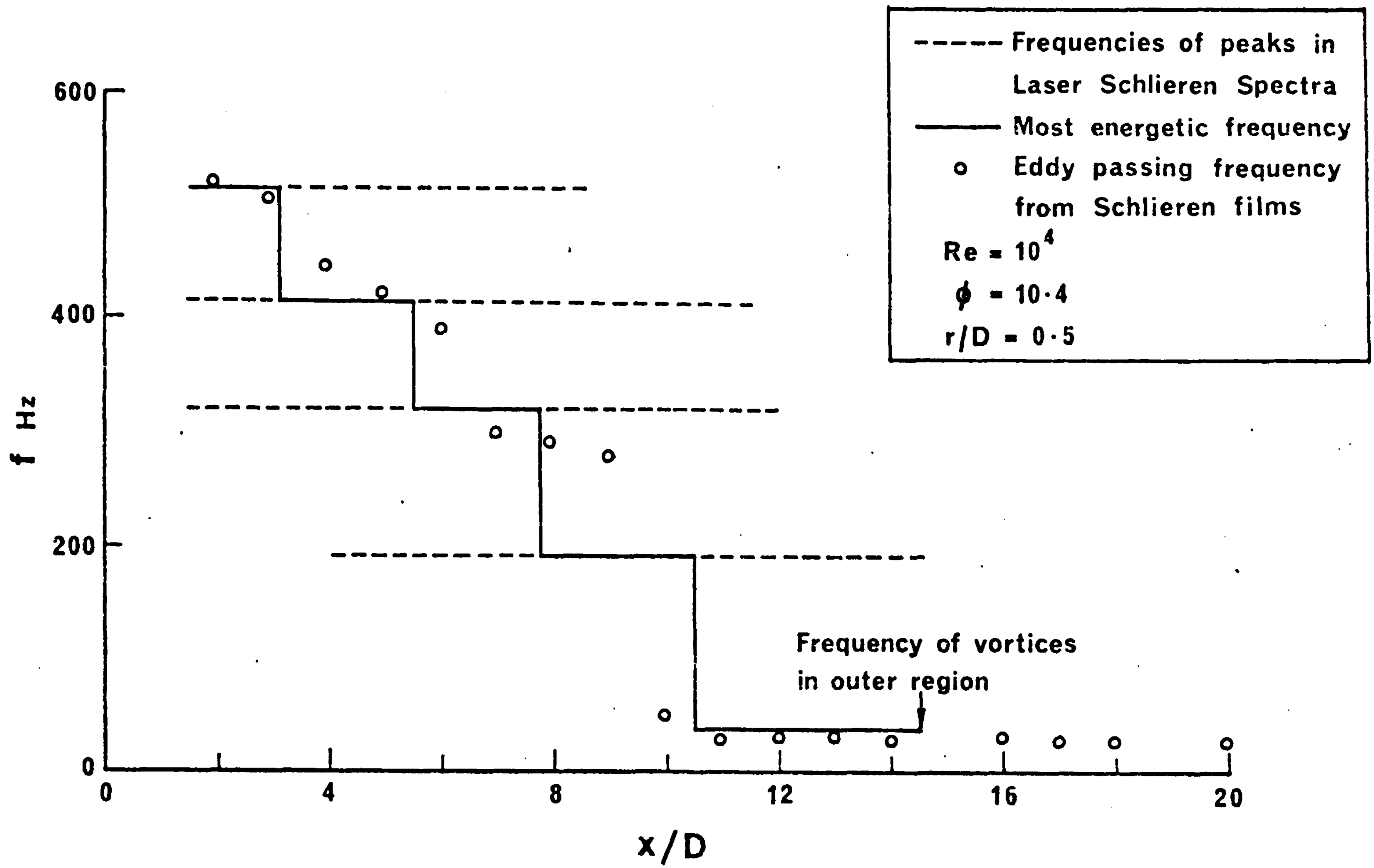
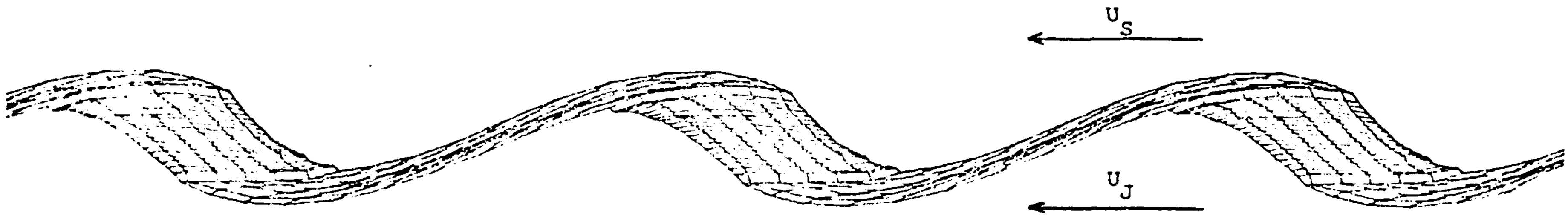
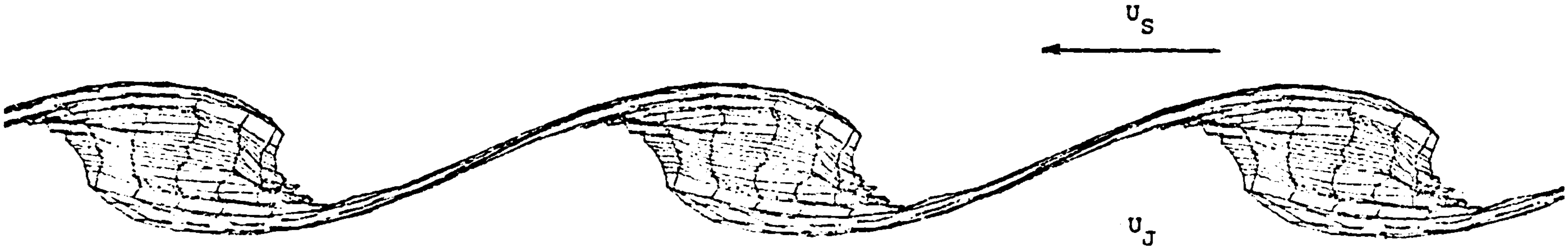


FIGURE 16. Peak frequencies in Laser Schlieren spectra compared with eddy passing frequencies measured independently, from high speed cine films.



TIME DELAY $\Delta t \, (U_J + U_S)/2D = 0.05$



TIME DELAY $\Delta t \, (U_J + U_S)/2D = 0.08$

FIGURE 17. Computer model of cylindrical mixing layer instability at two time delays after initial disturbance.

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